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DETERMINATION OF THE EFFECT OF STRAIN RATE ON THE
MECHANICAL PROPERTIES O..(U) NAVAL AIR DEVELOPMENT
CENTER WARMINSTER PA AIRCRAFT AND CREW S.. J M ALPER
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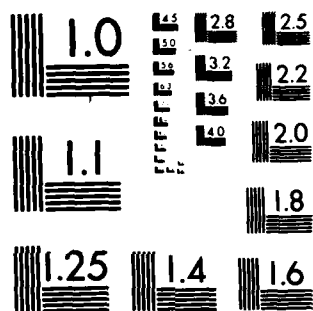
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**DETERMINATION OF THE EFFECT OF STRAIN RATE
ON THE MECHANICAL PROPERTIES OF
GRAPHITE/EPOXY LAMINATES**

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NAVAL AIR DEVELOPMENT CENTER
Warminster, PA 18974

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temperature wet environment and that laminates typical for Navy aircraft have a statistically significant strain rate effect only under the elevated temperature wet condition. ←

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FOREWORD

This is the final report for the program entitled "Determination of the Effect of Strain Rate on the Mechanical Properties of Graphite/Epoxy Laminates."

The project was initiated by Mr. M. Rosenfeld, who was the principal investigator from October 1980, to September 1981. Dr. J. Alper was the principal investigator for the remainder of the program, October 1981, to September 1982.

The author expresses appreciation to Mr. M. Corrigan and Mr. R. Dalrymple for their efforts on specimen testing.

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INTRODUCTION

Graphite/epoxy composites are commonly used on Navy aircraft to reduce the weight of the structure and improve performance. As the aircraft are subjected to flight maneuvers, stresses and strains occur in the various components, dependent on the maneuver. The rate at which the stresses and strains are applied varies with the speed at which the maneuvers occur. Strain rates up to 5000 μ strain/sec. can be encountered during flight. It is possible that a given component was designed from information generated at a much slower or faster strain rate than it actually experiences. If the strength of the material is strain rate dependent, a component could be unconservatively designed. Consider for example, a study by Ryder and Walker⁽¹⁾. It was found that some graphite/epoxy coupons subjected to fatigue cycling failed in the first cycle at tensile strengths much less than those expected from static tensile testing of the same laminate. The strain rate for the fatigue test in these cases was at least 100 times greater than the strain rate for the static test. In the laboratory it is common to run fatigue tests in which composite coupons experience 100,000 μ strain/sec., while static tests are conducted at 100 μ strain/sec.

Also, considering that fatigue specimens tested at a high frequency are subject to strain rates which are higher than strain rates in specimens fatigued at lower frequencies, it can be speculated that strain rate sensitivity may have an effect on the fatigue life of graphite/epoxy laminates. It has been shown that under constant amplitude fatigue, specimens tested at one frequency can show life times three or four times greater than specimens tested at a different frequency (2-5).

The purpose of this research program was to experimentally investigate the effect of strain rate on the static strength of graphite/epoxy laminates.

In particular, layups were used representative of both fiber-dominated and matrix-dominated laminates. Specimens were tested statically at strain rates typical of those experienced by aircraft in flight and at rates commonly used in the laboratory.

Exposure to certain environments, such as high temperature and high humidity, can affect the strength of graphite/epoxy. To investigate this effect, both room temperature dry and elevated temperature wet (200°F, 1% moisture content) specimens were tested in this program.

EXPERIMENTAL PROCEDURE

TEST SPECIMENS

The specimens used in this program were fabricated by the Martin Marietta Corporation using AS-3501-6 material. Four graphite/epoxy laminates were used representing both fiber and matrix dominated layups: Laminate 1, $[0^\circ]_{24T}$; Laminate 2, $[\pm 45]_{12S}$; Laminate 3, $[(\pm 45/0)_2]_3 / 90^\circ S$; and Laminate 4, $[(\pm 45/0/\pm 45)_2 / \pm 45/90] S$. Laminates 3 and 4, respectively, represent typical fiber and matrix dominated layups used on Navy aircraft, and Laminates 1 and 2, respectively, are extreme cases of fiber and matrix-dominated layups which are used here to better emphasize any trends which may appear in the other two laminates.

A 25.4 mm (1 in) wide specimen with a 6.35 mm (0.25 in) diameter center hole, as shown in Figure 1, was used for strain rate testing both in tension and compression. An identical specimen without the center hole was used for material characterization. The center hole specimen insures that failure occurs at the middle of the specimen and not at the end tab. Specimens were reinforced with glass fiber reinforced plastic end tabs to prevent buckling under compression loading (see Figure 1).

EQUIPMENT

All specimens were tested in a MTS closed-loop servo-hydraulic test machine equipped with "Alignomatic" self-aligning hydraulic grips. Tests conducted at strain rates of 35000 $\mu\text{strain/sec.}$ or faster were monitored using a Nicolette digital oscilloscope. Tests at slower strain rates were monitored using a Hewlett Packard X-Y plotter.

TEST PROCEDURE

Twenty-four unnotched specimens were statically tested to determine initial strain rate behavior for the four laminates as a function of load rate. The MTS machine used in these tests had only load control. The test plan for these specimens is shown in Table I. Based on this information, strain rates were chosen for each laminate to provide failure times of 100 sec., 10 sec., 1 sec., and .1 sec. These represent strain rates in the approximate range of 100 $\mu\text{strain/sec.}$ to 100,000 $\mu\text{strain/sec.}$ and encompass those values that occur during laboratory static testing, maximum maneuver, and gust loads of Navy aircraft in flight, as well as typical laboratory fatigue testing and vibration loading in flight. The actual strain rate and number of specimens used in each case are shown in Table II.

ENVIRONMENTAL CONDITIONS

Specimens were tested both at room temperature dry (RTD) and elevated temperature wet (ETW: 200°F, 1% moisture content) conditions. The RTD environment is a standard environment for evaluating material properties, and the ETW condition is about the most severe environment that the graphite/epoxy would be exposed to on the aircraft. In the latter environment (200°F, 1% moisture content), matrix-dominated laminates may lose up to 20% of their RTD static strength.

Specimens for the ETW test were in an environmental chamber 44 days at 170°F and 90% R.H. to obtain 1% moisture content. Traveler specimens 25.4 mm (1 in) x 25.4 mm (1 in) with a 6.35 mm (0.25 in) diameter hole and two edges blocked off by lead tape were used to monitor the moisture content. The lead tape prevented moisture from entering those edges.

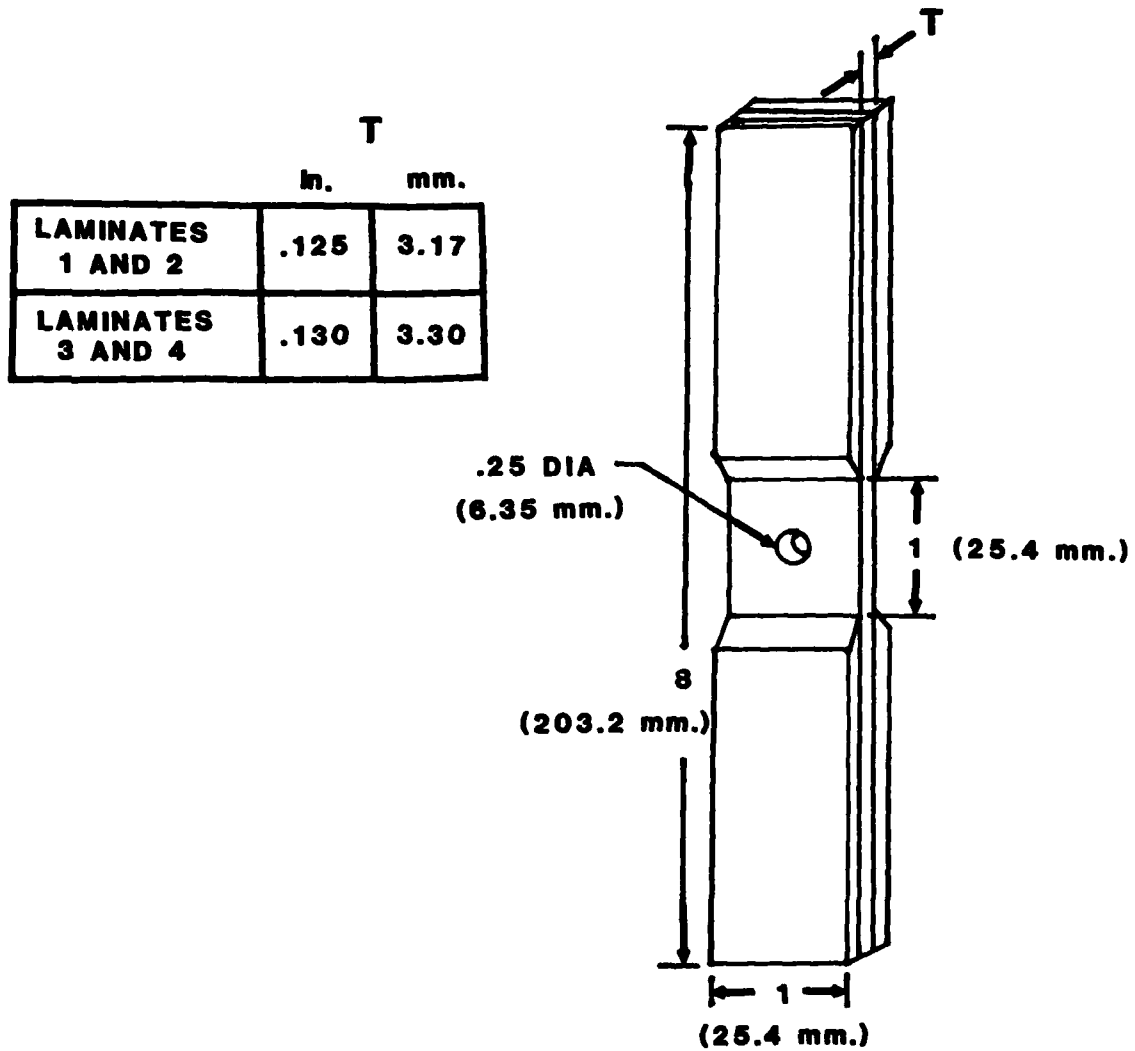


Figure 1. SPECIMEN GEOMETRY

TABLE I: TEST PLAN FOR UNNOTCHED SPECIMENS

A. RTD

Case	Laminate (1)	Test Rate (lb/sec)	Maximum Strain Before Unloading Specimen (μ strain)
1	2, 4	20	2000
2	1, 2, 3, 4	200	2000
3	1, 2, 3, 4	2000	2000
4	1, 3	20000	2000
5	1, 2, 3, 4	200	Reload all specimens from Case 2 to failure.

B. ETW (2)

Case	Laminate (1)	Test Rate (lb/sec)	Maximum Strain
1	1, 2, 3, 4	200	Test to failure
2	1, 2, 3, 4	2000	Test to failure

- (1) Two specimens were tested from each laminate listed at each test rate: one in tension, and one in compression.
- (2) These specimens were subjected to the RTD tests to 2000 μ strain in Part A.

TABLE II. TEST PLAN FOR NOTCHED SPECIMENS (1)

Laminate (2)	Test Condition (3)	Strain Rate (μ strain/sec.): No. of specimens Based on Time to Failure			
		.1 sec.	1 sec.	10 sec.	100 sec.
1	RTD-T	200000:10(4)	9600:7	960:7	96:10
1	RTD-C	71300:10	7130:7	713:7	71.3:10
1	ETW-C	35000:9	3500:7	350:7	35:9
2	RTD-T	148000:10	14800:7	1480:7	148:10
2	ETW-T	193000:10	—	—	193:10
2	RTD-C	96500:10	9650:7	965:7	96.5:10
2	ETW-C	77000:9	—	—	77:10
3	RTD-T	142000:10	14200:7	1420:7	142:10
3	ETW-T	144000:11	—	—	144:11
3	RTD-C	65300:10	6530:7	653:7	65.3:10
3	ETW-C	43500:11	—	—	43.5:11
4	RTD-T	214000:10	21400:7	2140:7	214:10
4	ETW-T	141000:11	—	—	141:11
4	RTD-C	98700:10	9870:7	987:7	98.7:10
4	ETW-C	61500:10	—	—	61.5:9

- (1) Does not include specimens that failed due to end tab failure or machine malfunction.
- (2) Laminate 1 — (0)₂₄T , Laminate 2 — (± 45)₁₂S ,
 Laminate 3 — [($\pm 45/0_2$)₃/ $\overline{90}$]_s ,
 Laminate 4 — [($\pm 45/0/\pm 45$)₂/ $\pm 45/\overline{90}$]_s
- (3) RTD — room temperature dry, ETW — elevated temperature wet (200°F, 1% moisture content), T - tension, C - compression
- (4) 200000 was used instead of 96000 because of an improper machine setting during the actual test.

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Prior to testing, the specimens were removed from the environmental chamber and placed directly in the MTS grips. A quartz lamp was used to bring the temperature of the specimen up to 200°F. A thermocouple attached to the back of the specimen was used to monitor the temperature. Insulation placed around the load cell and grips of the test machine ensured that machine accuracy would not be affected by the testing temperature. As soon as the specimen achieved the desired temperature, the test was started.

TEST RESULTS AND DISCUSSION

SUMMARY OF UNNOTCHED SPECIMENS

The unnotched specimens were used to characterize the material and develop a relationship between strain rate and time to failure. Table III shows the material characteristics for both RTD and ETW conditions. Appendix A contains a detailed presentation of the data. This information was used to extrapolate the relationship between initial strain rate and time to failure that was shown in the Test Plan, Table II.

SUMMARY OF NOTCHED SPECIMENS

Notched specimens were tested according to the Test Plan shown in Table II. Results for the RTD tests and ETW tests including the mean strength and standard deviation are shown, respectively, in Tables IV and V. All statistics are based on the normal distribution. Raw data for each test are presented in Appendix B.

DISCUSSION OF RESULTS

Results from the tests are presented in Figures 2 through 9. Each plot shows the statistical information generated from the tension and compression testing for each laminate. The mean \pm one standard deviation is plotted for each strain rate tested. A linear regression fit is used as an indicator for the behavior of the means as the strain rate changes. Table VI represents the results of statistical significance testing. Statistical significance testing is used to determine if samples from the same laminate under identical test conditions except the strain rate (i.e. Laminate 1, RTD, tension) are from the same population. The method used for significance testing was taken from MIL-HNBK 5 (6).

Figure 2 represents the RTD data for Laminate 1 (100/0/0). In tension, the trend of the means indicates an increase in strength as the strain rate decreases, while in compression there is an increase in strength as the strain rate increases. These trends may be due to the matrix behavior, since cracks have more time to grow at slower strain rates. Under tension load, cracking could allow misaligned or kinked fibers to straighten out, while under compression loading cracking could lead to greater buckling due to increased local instabilities. The results shown in Table VI indicate a statistically significant strain rate effect in compression but not in tension.

RTD data for Laminate 2 (0/100/0) is presented on Figure 3. Based on the linear regression fit of the means, the strength increases as the strain rate increases for both tension and compression. Since this is a matrix dominated layup, crack growth at slower strain rates could lead to earlier failures. The significance test in Table VI indicates a statistically significant effect for Laminate 2 under tension but not compression.

Results of the fiber-dominated Laminate 3 (48/48/4) at the RTD condition are shown in Figure 4. Although there is a slight tendency toward increased strength at slower strain rates for both tension and compression, neither case is statistically significant.

For the matrix-dominated Laminate 4 (16/80/4) at RTD, the results shown in Figure 5 indicate an increased strength at the faster strain rates in tension and at the slower strain rates in compression. However, neither case is statistically significant.

TABLE III: EXPERIMENTAL RESULTS OF UNNOTCHED SPECIMENS

A. Tension

Laminate	Modulus, E _x (MSI (GPa))		Poisson Ratio ν_{xy}	Ultimate Strength KSI (MPa)	
	RTD	ETW		RTD	ETW
1 (100/0/0)	20.4(141)	18.8(130)	.33	190(1310)	180(1241)
2 (0/100/0)	2.9(20)	1.3(9)	.83	43(296)	31(214)
3 (48/48/4)	10.0(69)	10.4(72)	.57	136(938)	125(862)
4 (16/80/4)	5.5(38)	4.8(33)	.69	83(572)	72(496)

B. Compression

Laminate	Modulus, E _x (MSI (GPa))		Poisson Ratio ν_{xy}	Ultimate Strength (KSI (MPa))	
	RTD	ETW		RTD	ETW
1 (100/0/0)	16.7(115)	19.3(133)	.29	83(572)	68(469)
2 (0/100/0)	2.4(17)	1.7(12)	.72	23(159)	15.5(107)
3 (48/48/4)	8.3(57)	10.0(69)	.49	52(359)	45(310)
4 (16/80/4)	4.9(34)	5.3(37)	.59	45(310)	34(234)

TABLE IV: RESULTS OF RTD NOTCHED SPECIMENS

A. Tension

Laminate	Strain Rate $\mu\text{strain/sec}$	Mean Strength X, KSI, (MPa)	Standard Deviation σ , KSI (MPa)
1 (100/0/0)	200000	271(1868)	15.8(109)
1	9600	283(1951)	13.1(90)
1	960	280(1930)	21.2(146)
1	96	293(2020)	21.4(148)
2 (0/100/0)	148000	35(241)	0.6(4.1)
2	14800	34(234)	0.71(4.9)
2	1480	33(228)	0.51(3.5)
2	148	32(221)	0.77(5.3)
3 (48/48/4)	142000	94(648)	4.9(33.8)
3	14200	98(676)	2.7(18.6)
3	1420	95(655)	4.4(30.3)
3	142	97(669)	2.3(15.9)
4 (16/80/4)	214000	55(379)	2.5(17.2)
4	21400	54(372)	1.2(8.3)
4	2140	53(365)	1.3(9.0)
4	214	53(365)	1.5(10.3)

B. Compression

Laminate	Strain Rate $\mu\text{strain/sec}$	Mean Strength X, KSI (MPa)	Standard Deviation σ , KSI (MPa)
1 (100/0/0)	71300	-92(-634)	10.1(70)
1	7130	-95(-655)	3.5(24)
1	713	-95(-655)	2.9(20)
1	71.3	-84(-579)	10.1(70)
2 (0/100/0)	96500	-34(-234)	5.2(36)
2	9650	-31(-214)	1.9(13)
2	965	-31(-214)	2.3(16)
2	96.5	-33(-228)	3.1(21)
3 (48/48/4)	65300	-70(-483)	4.5(31)
3	6530	-68(-469)	4.9(34)
3	653	-72(-496)	5.1(35)
3	65.3	-74(-510)	2.9(20)
4 (16/80/4)	98700	-47(-324)	5.4(37)
4	9870	-46(-317)	5.2(36)
4	987	-51(-352)	3.4(23)
4	98.7	-49(-338)	2.6(18)

TABLE V: RESULTS OF ETW NOTCHED SPECIMENS

A. Tension

Laminate	Strain Rate $\mu\text{strain/sec}$	Mean Strength X, KSI (MPa)	Standard Deviation σ , KSI (MPa)
2 (0/100/0)	193000	29(200)	1.4(10)
2	193	29(200)	0.84(6)
3 (48/48/4)	144000	114(786)	5.9(41)
3	144	116(800)	5.7(39)
4 (16/80/4)	141000	52(359)	1.2(8)
4	141	50(345)	1.6(11)

B. Compression

Laminate	Strain Rate $\mu\text{strain/sec}$	Mean Strength X, KSI (MPa)	Standard Deviation σ , KSI (MPa)
1 (100/0/0)	35000	-59(-407)	13.0(90)
1	3500	-51(-352)	3.2(22)
1	350	-48(-330)	4.9(34)
1	35	-44(-303)	2.9(20)
2 (0/100/0)	77000	-20(-138)	1.04(7)
2	77	-16(-110)	0.67(5)
3 (48/48/4)	43500	-48(-331)	3.7(26)
3	43.5	-42(-290)	3.3(23)
4 (16/80/4)	61500	-32(-221)	2.3(16)
4	61.5	-26(-179)	.92(6)

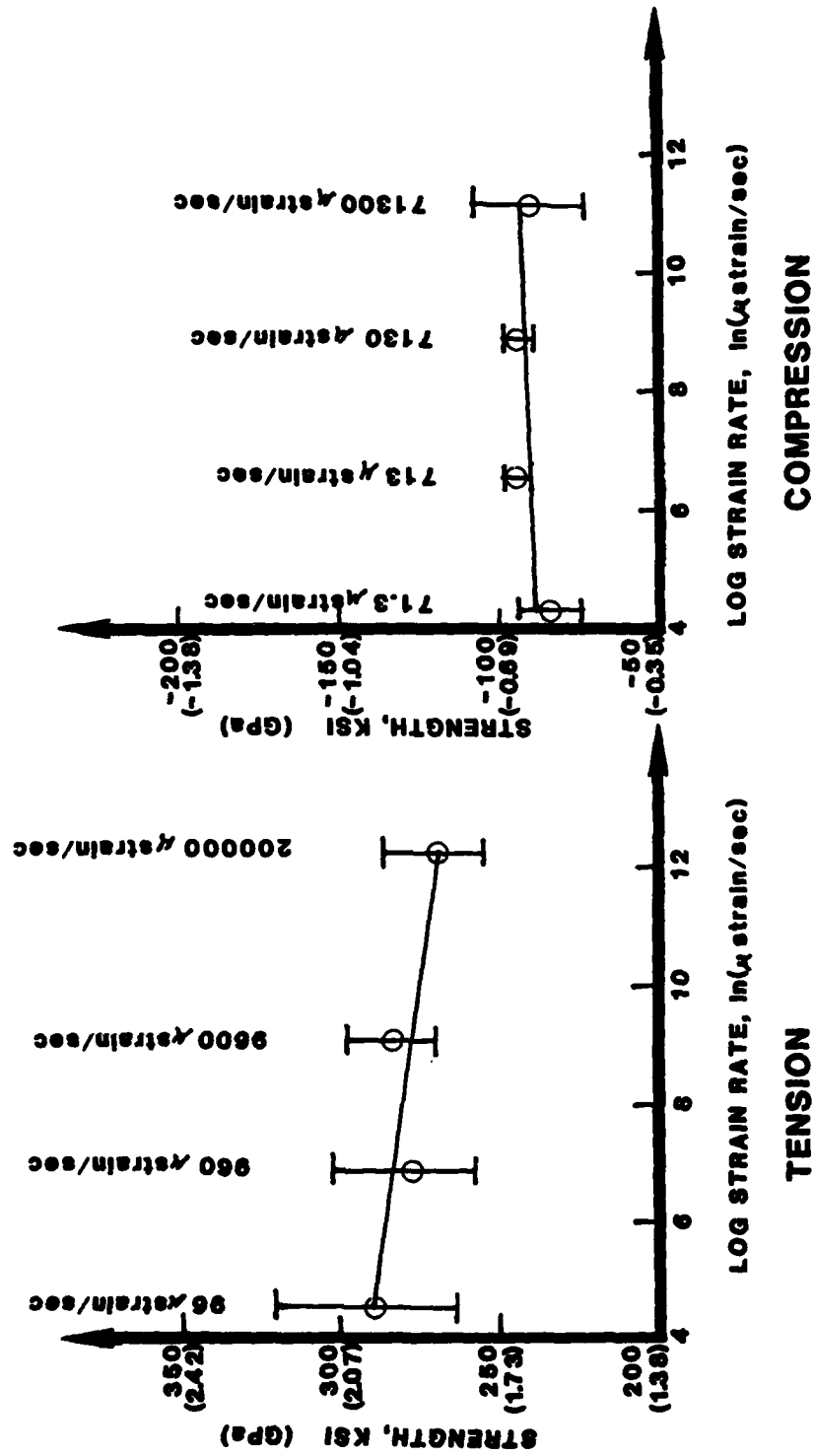


Figure 2. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 1 (100/0/0) RTD

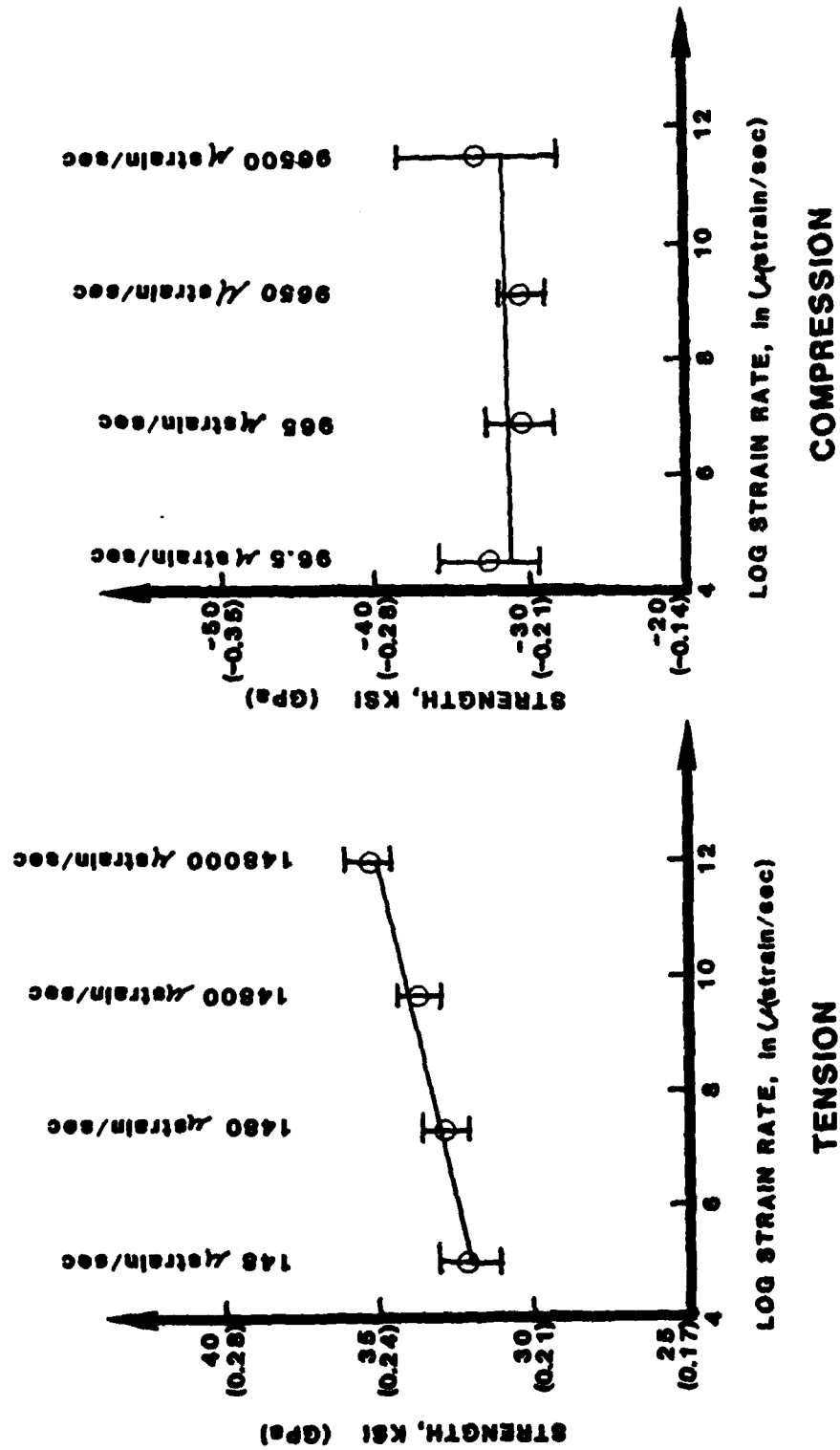


Figure 3. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 2 (0/100/0) RTD

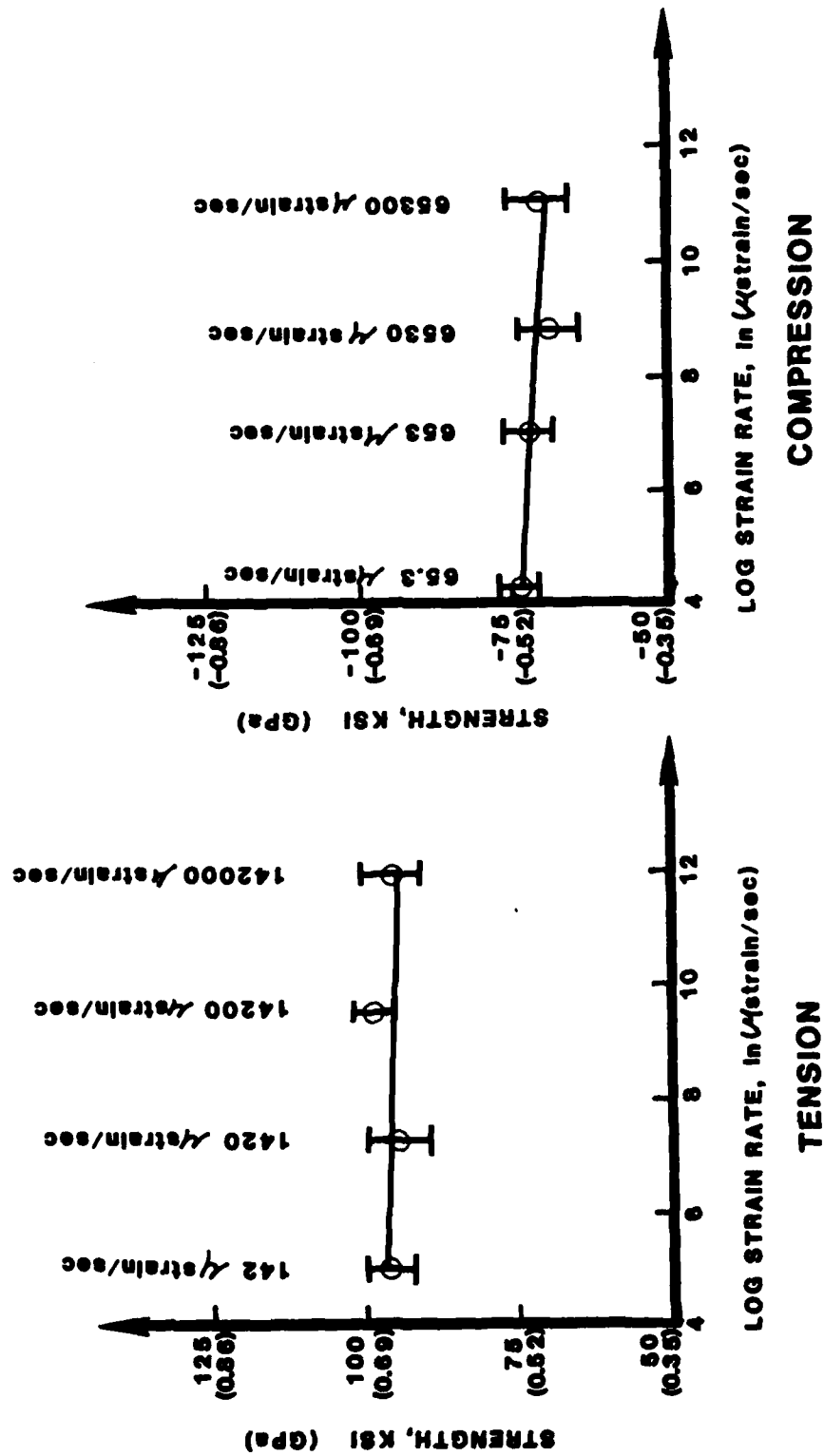


Figure 4. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 3 (48/48/4) RTD

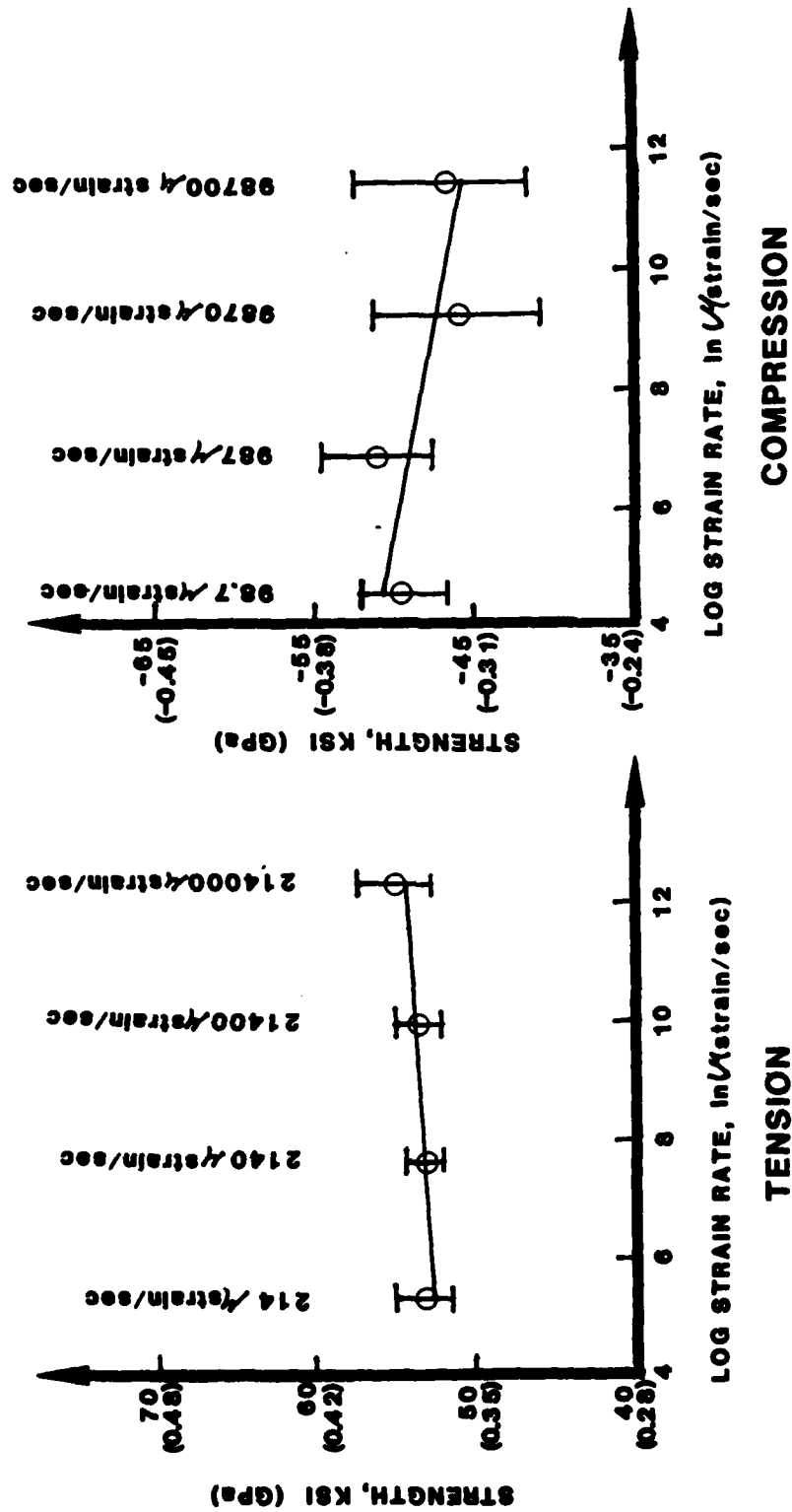


Figure 5. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 4 (16/80/4) RTD

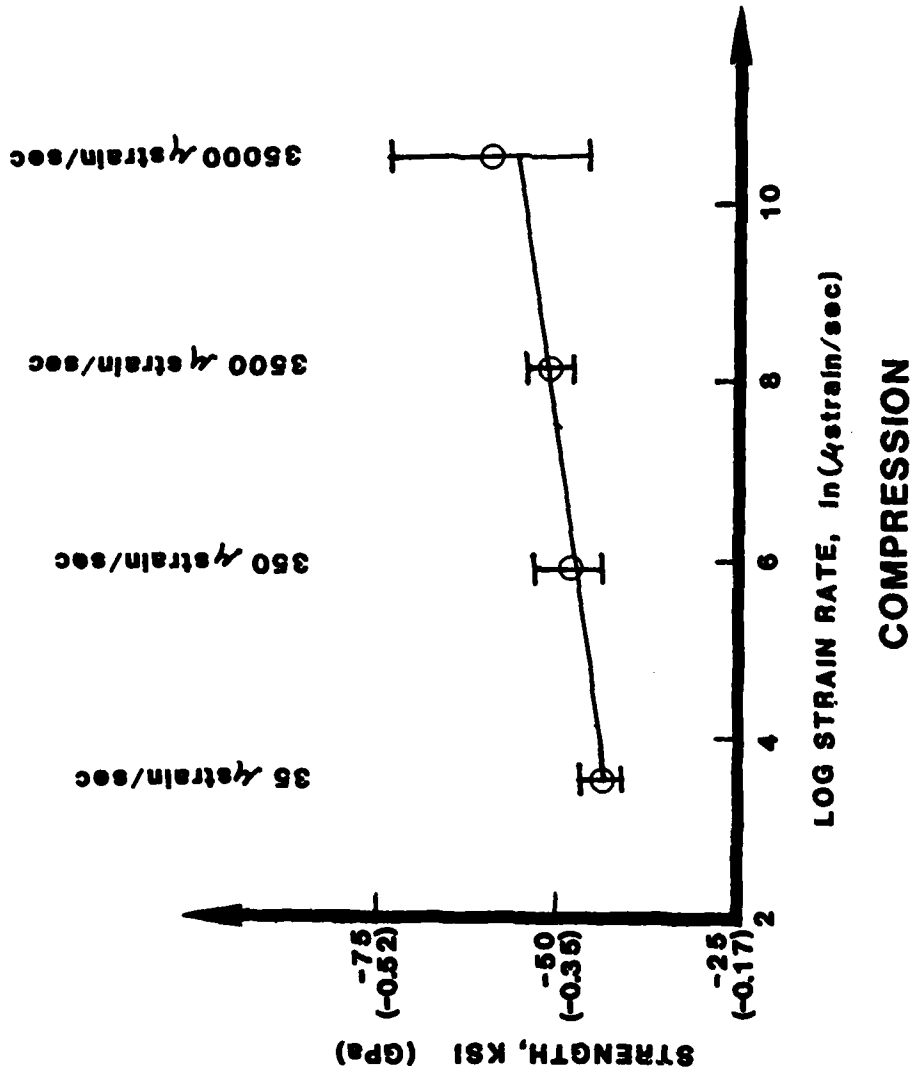


Figure 6. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 1 (100/0/0) ETW

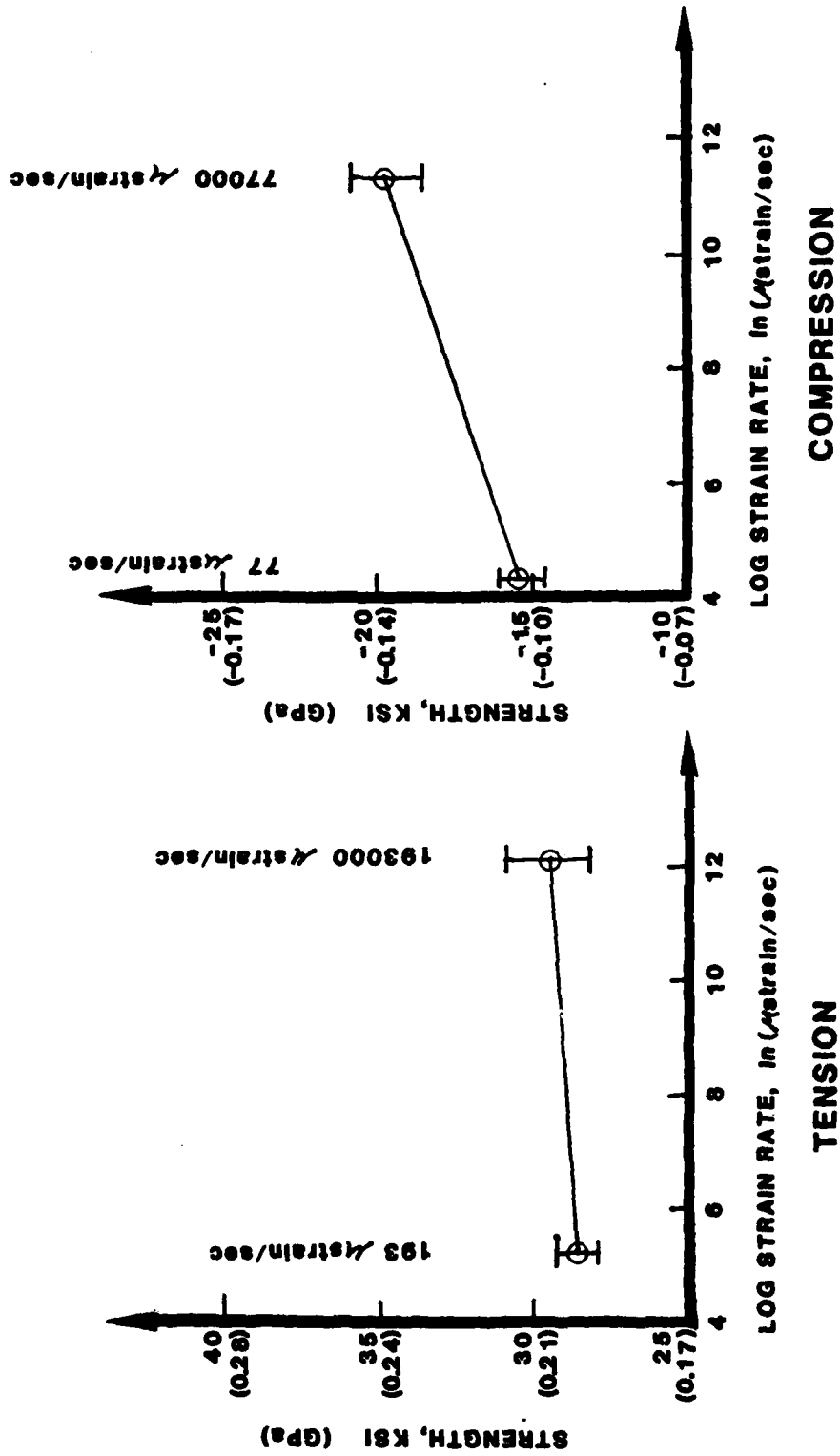


Figure 7. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 2 (0/100/0) ETW

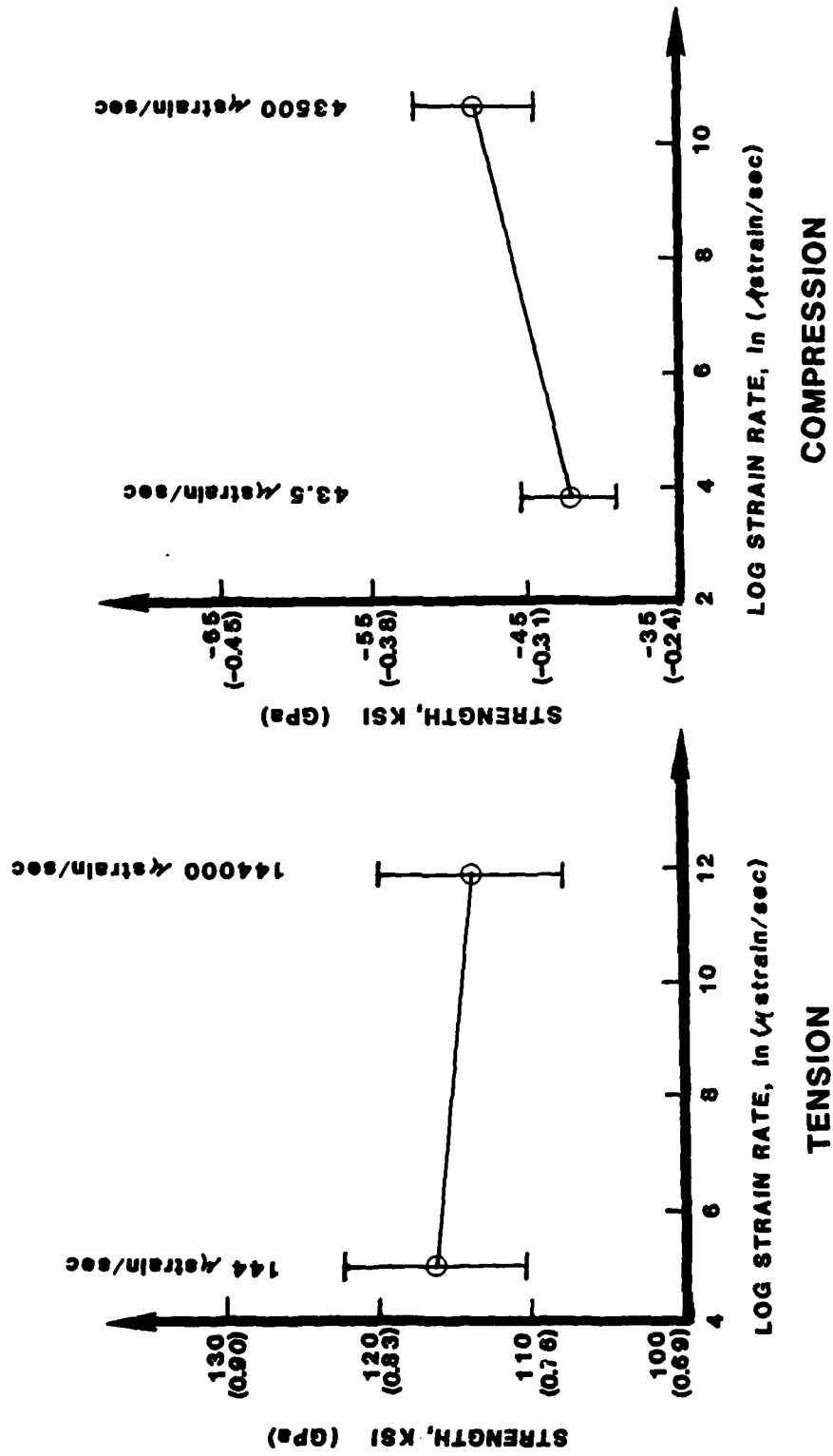


Figure 8. MEAN STRENGTH \pm STANDARD DEVIATION
LAMINATE 3 (48/48/4) ETW

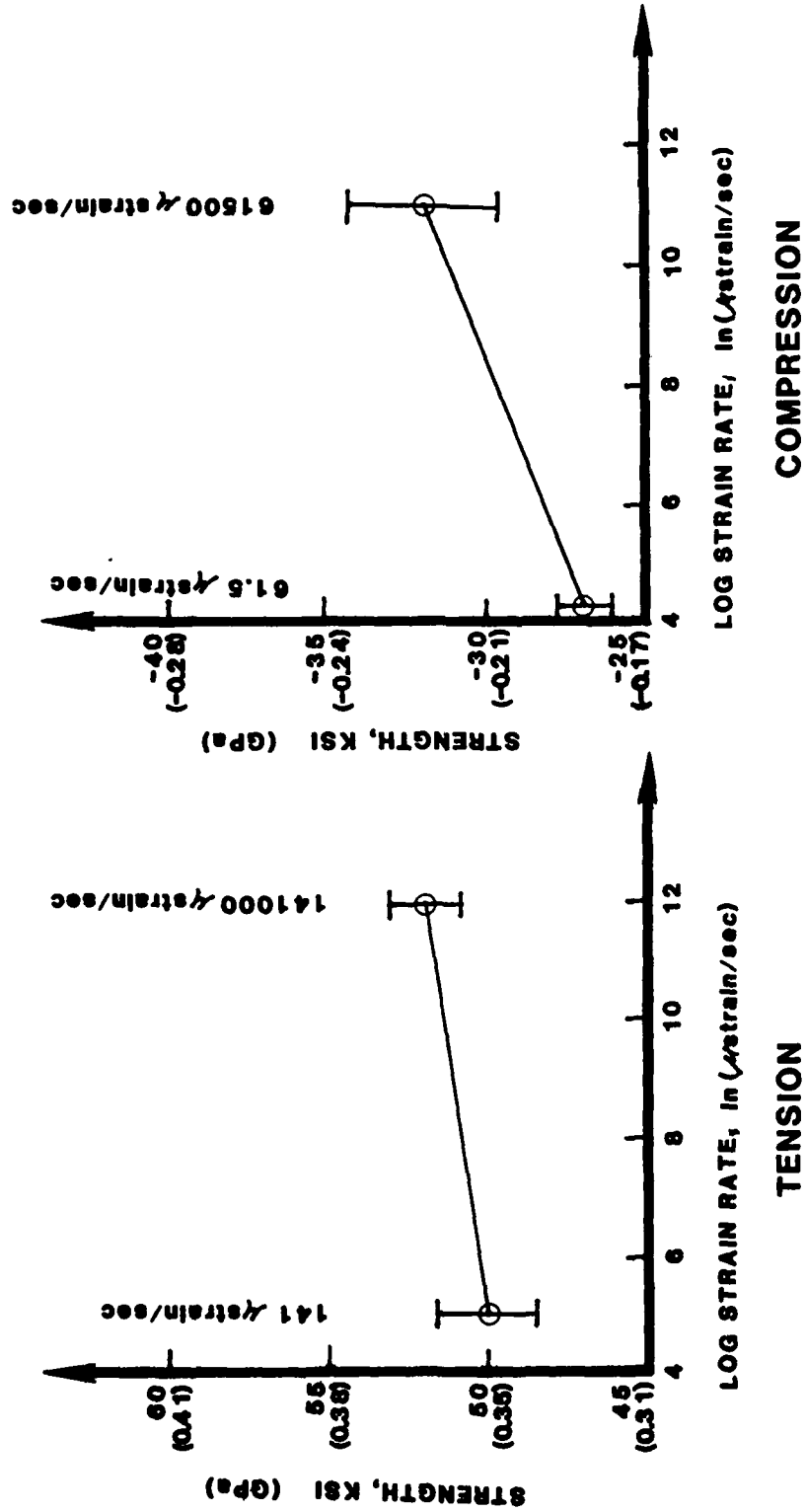


Figure 9. MEANS STRENGTH \pm STANDARD DEVIATION
LAMINATE 4 (16/80/4) ETW

TABLE VI: RESULTS OF SIGNIFICANCE TEST

Laminate	Tension or Compression (T or C)	ETW or RTD	Based on time to failure (sec), are the two samples from the same population:					
			.1&1	.1&10	.1&100	1&10	1&100	10&100
1 (100/0/0)	T	RTD	Yes	Yes	No	Yes	Yes	Yes
1	C	RTD	No	No	Yes	Yes	No	No
1	C	ETW	No	No	No	Yes	No	Yes
2 (0/100/0)	T	RTD	No	No	No	No	No	Yes
2	C	RTD	No	Yes	Yes	Yes	Yes	Yes
2	T	ETW	—	—	Yes	—	—	—
2	C	ETW	—	—	No	—	—	—
3 (48/48/4)	T	RTD	Yes	Yes	No	Yes	Yes	Yes
3	C	RTD	Yes	Yes	No	Yes	No	Yes
3	T	ETW	—	—	Yes	—	—	—
3	C	ETW	—	—	No	—	—	—
4 (16/80/4)	T	RTD	Yes	Yes	Yes	Yes	Yes	Yes
4	C	RTD	Yes	Yes	No	Yes	Yes	Yes
4	T	ETW	—	—	No	—	—	—
4	C	ETW	—	—	No	—	—	—

At the RTD condition, the two laminates representative of those found on Navy aircraft (Laminates 3 and 4) do not indicate any statistically significant trends due to changes in strain rate.

At the ETW condition, Laminate 1 shows increased strength at the quicker strain rates for compression testing, Figure 6. From Table VI, it can be seen that these results are statistically significant.

Laminate 2 under the ETW condition also shows increased strength at the faster strain rates for both tension and compression, Figure 7. The results are statistically significant for compression but not in tension.

Prior to testing, it seemed plausible that the ETW environment would worsen any effects of strain rate seen at the RTD condition. Under tension testing, matrix dominated Laminate 2 showed results that were statistically significant for RTD but not for ETW, which disproves the above assumption.

Laminate 3 under the ETW condition, Figure 8, is stronger at the slower strain rate in tension and at the faster strain rate in compression. The strain rate effect in compression is statistically significant but not for the tension case. It is interesting to note that the trend of the compression behavior is different between RTD and ETW. RTD shows increased strength at slower strain rates while ETW shows increased strength at faster strain rates. Perhaps matrix degradation due to the ETW environment reduces the strength contribution from the 0° layers at slower strain therefore allowing this change in behavior.

Results of Laminate 4 at the ETW condition are shown in Figure 9. Both tension and compression cases showed increased strength at the faster strain rates. As shown in Table VI, both cases are statistically significant. With this laminate, as was the case with Laminate 3, the trend of the compression behavior is different for the ETW and RTD conditions. At RTD there is increased strength at the slower strain rate, and at ETW there is increased strength at the quicker strain rates.

SUMMARY AND CONCLUSIONS

The strain rate sensitivity of four laminates has been experimentally evaluated for both static tension and compression at two different environments, RTD and ETW (200°F, 1% moisture content). The layups were: Laminate 1, $[0]_{24T}$; Laminate 2, $[\pm 45]_{12S}$; Laminate 3, $[(\pm 45/0)_2]_3 / 90_S$; and Laminate 4, $[(\pm 45/0/\pm 45)_2 / \pm 45/90]_S$. Strain rates used for RTD testing were chosen to simulate failure times of .1 sec., 1 sec., 10 sec., and 100 sec. For ETW tests, strain rates were chosen to simulate failure times of .1 sec. and 100 sec.

RTD Tests: Based on the linear regression fit of the mean strengths, the following trends appear:

Tension

- 1) Matrix-dominated layups (Laminates 2 and 4) are stronger at faster strain rates.
- 2) Fiber-dominated layups (Laminates 1 and 3) are stronger at slower strain rates.

Compression

- 1) Laminates 1 and 2 are stronger at faster strain rates.
- 2) Laminates 3 and 4 are stronger at slower strain rates.

Significance testing of the means and standard deviations indicate that there was a statistically significant strain rate effect on only two cases, Laminate 1 (compression) and Laminate 2 (tension). Both have matrix-dominated failure modes.

ETW Tests: Based on the linear regression fit of the mean strengths, the following trends appear:

Tension

- 1) Matrix-dominated layups (Laminates 2 and 4) are stronger at faster strain rates.
- 2) Fiber-dominated layup (Laminate 3) is stronger at the slower strain rate.

Compression

- 1) All laminates are stronger at the faster strain rates. Significance testing of the means and standard deviations indicate that strain rate had a statistically significant effect on matrix-dominated Laminate 4 in tension and on all of the laminates in comparison.

Apparently, the matrix degradation that occurs during exposure to the ETW environment makes the laminates more strain rate sensitive than the RTD environment.

Laminates common to Navy aircraft (Laminate 3 and 4) show statistically significant strain rate effects only under the ETW environment. Compression testing was most severe indicating increases in mean strength of 16.5% for Laminate 3 and 12.5% for Laminate 4 at the faster strain rates. However, since ultimate strength testing is conducted in the range of strain rates which yielded lower strengths for typical Navy laminates, the results of this program indicate that static test data used for aircraft design is conservative.

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APPENDIX A
MATERIAL CHARACTERIZATION

APPENDIX A: MATERIAL CHARACTERIZATION

A. RTD - Specimens

Specimen	Max. Stress prior to unloading, KSI (MPa)	Max. Strain prior to unloading, μ strain	Load Rate, lb/sec (kN/sec)	Time to Max. Strain, sec.	Initial Modulus, Ex, MSI (GPa)	Poisson Ratio ν_{xy}	Initial Strain Rate, μ strain/sec.
IL3	37.7 (260)	1900	200 (.89)	23.5	20.3 (140)	0.30	80.9
1E1	37.7 (260)	1850	2000 (8.9)	2.35	20.7 (143)	0.39	787
1D4	37.7 (260)	1900	20000 (89)	.34	20.2 (139)	0.32	5590
2G3	4.3 (29.6)	1487	20 (.089)	32.6	2.9 (20)	0.82	45.7
2A2	4.3 (29.6)	1487	200 (.89)	2.64	2.9 (20)	0.84	563
2F2	4.3 (29.6)	1475	2000 (8.9)	.31	2.9 (20)	0.84	4760
3A1	21.5 (148)	2112	200 (.89)	14.3	10.1 (70)	0.57	148
3J3	21.5 (148)	1950	2000 (8.9)	1.45	10.5 (72)	0.59	1340
3D1	21.5 (148)	2313	20000 (89)	.24	9.5 (66)	0.56	9720
4B5	10.6 (73)	1863	20 (.089)	97.0	5.8 (40)	0.70	19.2
4I6	10.6 (73)	1925	200 (.89)	6.9	5.3 (37)	0.71	281
4D8	10.6 (73)	1925	2000 (8.9)	.70	5.5 (38)	0.67	2750
1AF5	-31.5 (-217)	-2000	-20000 (-89)	.22	15.7 (108)	0.27	-9090
1AE2	-31.5 (-217)	-2033	-2000 (-8.9)	1.86	15.2 (105)	0.30	-1090
1AC6	-31.5 (-217)	-1600	-200 (-.89)	22.75	19.1 (132)	0.31	-70.3
2AA1	-4.2 (-29)	-1712	-2000 (-8.9)	.33	2.5 (17)	0.72	-5190
2HH5	-4.2 (-29)	-1742	-200 (-.89)	2.41	2.4 (17)	0.72	-723
2EE9	-4.2 (-29)	-1675	-20 (-.089)	29.6	2.4 (17)	0.73	56.6
3EE9	-17.8 (-123)	-2108	-20000 (-89)	.19	8.3 (57)	0.50	11153
3GG8	-17.8 (-123)	-2100	-2000 (-8.9)	1.03	8.2 (57)	0.49	-2040
3FF1	-17.8 (-123)	-2133	-200 (-.89)	10.8	8.3 (57)	0.47	-198
4AA1	-9.1 (-62.7)	-1783	-2000 (-8.9)	.54	5.2 (36)	0.60	-3300
4GG9	-9.1 (-62.7)	-1867	-200 (-.89)	5.25	4.8 (33)	0.60	-356
4EE9	-9.1 (-62.7)	-1925	-20 (-.089)	84.1	4.7 (32)	0.58	-22.9

(1) First digit of specimen no. indicates laminate (i.e. specimen no. 1L3 is from Laminate 1)

B. RTD - Failure Data (1)

<u>Specimen No.</u>	<u>Ultimate Strength KSI (MPa)</u>	<u>Time to Failure, sec.</u>	<u>Initial Strain Rate μstrain/sec.</u>
1L3	190 (1310)	73.8	80.9
2A2	43 (296)	31	563
3A1	136 (938)	135	148
4I6	83 (572)	48.2	281
1AC6	-83 (-572)	45.4	-70.3
2HH5	-23 (-159)	22	-723
3FF1	-52 (-359)	33	-198
4GG9	-45 (-310)	33	-356

(1) All specimens were previously subjected to test in part A.

C. ETW - Failure Data (1)

Specimen No.	Ultimate Strength KSI (MPa)	Time to Failure, sec.	Initial Strain Rate, μ strain/sec	Initial Modulus, Ex, MSI (GPa)
1E1	180 (1241)	212	35.7	18.8 (130)
1D4	81 (558) (2)	9.2	410	18.8 (130)
2F2	31.7 (219)	2.0	13440	1.19 (8.3)
2G3	30.8 (212)	19.8	975	1.38 (9.5)
3D1	139 (958)	9.9	Not available	Not available
3J3	111 (765) (2)	75	150	10.4 (71.7)
4B5	75.8 (523)	5.0	Not available	Not available
4D8	68.6 (473)	45.3	310	4.75 (32.7)
1AE2	-70.5 (-486)	43.4	-85	19.1 (132)
1AF5	-65.2 (-450)	4.2	-814	19.4 (134)
2EE9	-16.6 (-114)	8.3	-928	1.7 (11.7)
2AA1	-14.4 (-99)	1.0	Not Available	Not available
3EE9	-47.8 (-329)	3.0	-1450	10.6 (73)
3GG8	-42.2 (-291)	28.1	-154	9.4 (64.8)
4AA1	-32.5 (-224)	2.1	-2810	5.3 (36.5)
4EE9	-35.4 (-244)	23.0	-275	5.3 (36.5)

(1) All specimens were previously subjected to test in part A.

(2) End tab failure.

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APPENDIX B
STRENGTH OF NOTCHED SPECIMENS

APPENDIX B – STRENGTH OF NOTCHED SPECIMENS

A. LAMINATE NO. 1 (100/0/0)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 200000 μ STRAIN/SEC:
10 SPECIMENS

289 (1996)	262 (1809)	246 (1697)	242 (1670)
268 (1851)	257 (1777)	243 (1679)	
265 (1830)	247 (1709)	242 (1673)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9600 μ STRAIN/SEC:
7 SPECIMENS

287 (1983)	274 (1891)	270 (1863)	254 (1756)
282 (1947)	274 (1890)	265 (1833)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 960 μ STRAIN/SEC:
7 SPECIMENS

279 (1929)	273 (1887)	267 (1845)	218 (1503)
276 (1905)	272 (1880)	254 (1753)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96 μ STRAIN/SEC:
10 SPECIMENS

301 (2081)	280 (1935)	261 (1805)	231 (1598)
292 (2014)	277 (1912)	259 (1790)	
291 (2010)	265 (1833)	234 (1616)	

APPENDIX B - (continued)

B. LAMINATE NO. 1 (100/0/0)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 71300 μ STRAIN/SEC:
10 SPECIMENS

-99 (-680)	-93 (-637)	-84 (-577)	-73 (-499)
-99 (-679)	-92 (-633)	-80 (-546)	
-97 (-667)	-91 (-625)	-77 (-526)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 7130 μ STRAIN/SEC:
7 SPECIMENS

-96 (-662)	-92 (-629)	-89 (-613)	-86 (-593)
-93 (-641)	-91 (-621)	-89 (-608)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 713 μ STRAIN/SEC:
7 SPECIMENS

-93 (-640)	-92 (-634)	-89 (-609)	-86 (-593)
-93 (-638)	-92 (-632)	-88 (-601)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 71 μ STRAIN/SEC:
10 SPECIMENS

-92 (-633)	-84 (-578)	-76 (-518)	-65 (-443)
-90 (-621)	-83 (-571)	-72 (-497)	
-88 (-601)	-83 (-569)	-71 (-487)	

APPENDIX B – (continued)

C. LAMINATE NO. 1 (100/0/0)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 35000 μ STRAIN/SEC:
9 SPECIMENS

-89 (-613)	-60 (-410)	-55 (-377)
-66 (-451)	-58 (-397)	-48 (-327)
-63 (-431)	-56 (-381)	-44 (-300)

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 3500 μ STRAIN/SEC:
7 SPECIMENS

-54 (-371)	-53 (-361)	-51 (-346)	-45 (-308)
-54 (-369)	-52 (-354)	-49 (-336)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 350 μ STRAIN/SEC:
7 SPECIMENS

-54 (-373)	-50 (-345)	-48 (-328)	-41 (-280)
-53 (-364)	-49 (-332)	-43 (-294)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 35 μ STRAIN/SEC:
9 SPECIMENS

-48 (-330)	-46 (-313)	-42 (-285)
-47 (-319)	-45 (-305)	-41 (-279)
-46 (-318)	-44 (-303)	-40 (-270)

APPENDIX B -- (continued)

D. LAMINATE NO. 2 (0/100/0)

RTD TENSION TEST

- 1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 148000 μ STRAIN/SEC:
10 SPECIMENS

34 (237)	34 (234)	33 (232)	33 (228)
34 (235)	33 (233)	33 (230)	
34 (234)	33 (232)	33 (230)	

- 2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14800 μ STRAIN/SEC:
7 SPECIMENS

32 (226)	32 (225)	32 (222)	31 (218)
32 (225)	32 (223)	31 (220)	

- 3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 1480 μ STRAIN/SEC:
7 SPECIMENS

31 (219)	31 (215)	31 (214)	30 (213)
31 (217)	31 (215)	31 (213)	

- 4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 148 μ STRAIN/SEC:
10 SPECIMENS

30 (209)	30 (208)	30 (208)	29 (205)
30 (209)	30 (208)	30 (207)	
30 (208)	30 (208)	29 (205)	

APPENDIX B – (continued)

E. LAMINATE NO. 2 (0/100/0)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96500 μ STRAIN/SEC:
10 SPECIMENS

-43 (-292)	-33 (-224)	-31 (-212)	-23 (-155)
-34 (-231)	-32 (-219)	-30 (-205)	
-33 (-228)	-32 (-218)	-30 (-201)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9650 μ STRAIN/SEC:
7 SPECIMENS

-32 (-216)	-31 (-208)	-29 (-199)	-28 (-188)
-31 (-212)	-30 (-201)	-29 (-196)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 965 μ STRAIN/SEC:
7 SPECIMENS

-32 (-217)	-30 (-204)	-29 (-199)	-27 (-180)
-32 (-214)	-29 (-199)	-27 (-186)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96 μ STRAIN/SEC:
10 SPECIMENS

-33 (-225)	-33 (-222)	-32 (-217)	-24 (-161)
-33 (-224)	-33 (-222)	-31 (-211)	
-33 (-223)	-32 (-220)	-29 (-198)	

APPENDIX B — (continued)

F. LAMINATE NO. 2 (0/100/0)

ETW TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 193000 μ STRAIN/SEC:
10 SPECIMENS

31 (213)	30 (209)	28 (196)	27 (186)
30 (213)	30 (208)	28 (195)	
30 (209)	28 (196)	28 (193)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 193 μ STRAIN/SEC:
10 SPECIMENS

30 (206)	29 (201)	28 (195)	27 (190)
29 (205)	28 (197)	28 (193)	
29 (203)	28 (195)	27 (191)	

G. LAMINATE NO. 2 (0/100/0)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 77000 μ STRAIN/SEC:
9 SPECIMENS

-22 (-148)	-21 (-140)	-20 (-134)
-21 (-145)	-20 (-138)	-20 (-132)
-21 (-143)	-20 (-136)	-18 (-125)

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 77 μ STRAIN/SEC:
10 SPECIMENS

-17 (-114)	-16 (-111)	-16 (-105)	-15 (-99)
-17 (-112)	-16 (-109)	-15 (-104)	
-16 (-111)	-16 (-107)	-15 (-103)	

APPENDIX B – (continued)

H. LAMINATE NO. 3 (48/48/4)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 142000 μ STRAIN/SEC:
10 SPECIMENS

98 (677)	92 (637)	88 (606)	79 (545))
95 (659)	91 (629)	86 (598)	
93 (642)	90 (621)	85 (592)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14200 μ STRAIN/SEC:
7 SPECIMENS

93 (647)	91 (631)	89 (615)	87 (599)
93 (644)	91 (629)	88 (609)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 1420 μ STRAIN/SEC:
7 SPECIMENS

94 (651)	88 (610)	87 (605)	85 (592)
89 (618)	88 (609)	86 (597)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 142 μ STRAIN/SEC:
10 SPECIMENS

98 (677)	92 (638)	89 (619)	86 (598)
94 (653)	92 (637)	89 (616)	
94 (649)	91 (630)	88 (607)	

APPENDIX B — (continued)

I. LAMINATE NO. 3 (48/48/4)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 65300 μ STRAIN/SEC:
10 SPECIMENS

-73 (-502)	-66 (-449)	-64 (-437)	-60 (-414)
-69 (-470)	-65 (-449)	-63 (-434)	
-68 (-463)	-65 (-445)	-62 (-427)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 6530 μ STRAIN/SEC:
7 SPECIMENS

-75 (-515)	-64 (-436)	-63 (-431)	-61 (-414)
-67 (-460)	-63 (-432)	-61 (-418)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 653 μ STRAIN/SEC:
7 SPECIMENS

-72 (-491)	-71 (-485)	-69 (-471)	-62 (-424)
-71 (-486)	-69 (-474)	-64 (-435)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 65 μ STRAIN/SEC:
10 SPECIMENS

-72 (-491)	-70 (-481)	-69 (-475)	-67 (-458)
-72 (-491)	-70 (-479)	-69 (-475)	
-71 (-484)	-69 (-475)	-68 (-468)	

APPENDIX B - (continued)

J. LAMINATE NO. 3 (48/48/4)

ETW TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14400 μ STRAIN/SEC:
11 SPECIMENS

127 (875)	114 (790)	112 (774)	108 (750)
118 (819)	113 (781)	109 (754)	105 (723)
116 (803)	112 (777)	109 (752)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 144 μ STRAIN/SEC:
11 SPECIMENS

126 (871)	118 (817)	116 (800)	108 (749)
121 (834)	118 (816)	114 (792)	105 (728)
119 (823)	116 (800)	114 (789)	

K. LAMINATE NO. 3 (48/48/4)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 43500 μ STRAIN/SEC:
11 SPECIMENS

-55 (-374)	-50 (-343)	-47 (-325)	-44 (-304)
-54 (-369)	-50 (-340)	-46 (-313)	-44 (-298)
-50 (-345)	-49 (-338)	-45 (-308)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 43 μ STRAIN/SEC:
11 SPECIMENS

-50 (-342)	-43 (-296)	-42 (-285)	-39 (-264)
-45 (-306)	-43 (-296)	-41 (-282)	-38 (-257)
-43 (-296)	-43 (-293)	-40 (-275)	

APPENDIX B -- (continued)

L. LAMINATE NO. 4 (16/80/4)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 214000 μ STRAIN/SEC:
10 SPECIMENS

56 (391)	51 (355)	50 (344)	49 (341)
53 (366)	51 (351)	49 (342)	
52 (363)	50 (346)	49 (342)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 21400 μ STRAIN/SEC:
7 SPECIMENS

54 (377)	52 (360)	50 (348)	48 (336)
52 (363)	51 (355)	49 (343)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 2140 μ STRAIN/SEC:
7 SPECIMENS

52 (359)	50 (346)	49 (342)	48 (332)
51 (351)	49 (342)	49 (341)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 214 μ STRAIN/SEC:
10 SPECIMENS

51 (354)	50 (348)	49 (343)	48 (330)
51 (351)	50 (346)	49 (340)	
50 (348)	50 (345)	49 (340)	

APPENDIX B — (continued)

M. LAMINATE NO. 4 (16/80/4)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 98700 μ STRAIN/SEC:
10 SPECIMENS

-52 (-359)	-46 (-317)	-42 (-286)	-39 (-266)
-52 (-356)	-46 (-314)	-40 (-271)	
-49 (-332)	-43 (-292)	-39 (-268)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9870 μ STRAIN/SEC:
7 SPECIMENS

-49 (-333)	-47 (-324)	-42 (-289)	-36 (-247)
-49 (-332)	-45 (-308)	-39 (-267)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 987 μ STRAIN/SEC:
7 SPECIMENS

-53 (-361)	-49 (-336)	-48 (-328)	-44 (-301)
-51 (-351)	-49 (-332)	-47 (-319)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 99 μ STRAIN/SEC:
10 SPECIMENS

-49 (-336)	-47 (-320)	-47 (-318)	-42 (-288)
-48 (-330)	-47 (-318)	-46 (-311)	
-48 (-330)	-47 (-318)	-44 (-303)	

APPENDIX B — (continued)

N. LAMINATE NO. 4 (16/80/4)

ETW TENSION TEST

- 1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 141000 μ STRAIN/SEC:
11 SPECIMENS

53 (370)	52 (363)	51 (352)	50 (348)
53 (367)	52 (360)	51 (352)	50 (346)
53 (366)	52 (359)	51 (352)	

- 2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 141 μ STRAIN/SEC:
11 SPECIMENS

52 (360)	51 (353)	49 (341)	48 (333)
51 (357)	50 (348)	48 (335)	47 (329)
51 (355)	49 (341)	48 (333)	

O. LAMINATE NO. 4 (16/80/40)

ETW COMPRESSION TEST

- 1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 61500 μ STRAIN/SEC:
10 SPECIMENS

-35 (-236)	-34 (-229)	-32 (-216)	-27 (-183)
-34 (-231)	-32 (-220)	-31 (-209)	
-34 (-230)	-32 (-216)	-30 (-205)	

- 2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 61 μ STRAIN/SEC:
9 SPECIMENS

-28 (-191)	-27 (-185)	-27 (-180)
-28 (-189)	-27 (-184)	-26 (-178)
-27 (-187)	-27 (-182)	-25 (-170)

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